

# Geologic Resource Evaluation Scoping Summary White Sands National Monument

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The Geologic Resource Evaluation (GRE) Program provides each of 270 identified natural area National Park System units with a geologic scoping meeting and summary (this report), digital geologic map, and geologic resource evaluation report. Geologic scoping meetings generate an evaluation of the adequacy of existing geologic maps for resource management, provide an opportunity to discuss park-specific geologic management issues, and if possible include a site visit with local experts. The purpose of these meetings is to identify geologic mapping coverage and needs, distinctive geologic processes and features, resource management issues, and potential monitoring and research needs.

In 2003 the Geologic Resource Division (GRD) coordinated a Geoindicators scoping meeting for White Sands National Monument. This meeting was in response to a technical assistance request from park managers, who wanted input on the geologic resources at White Sands National Monument for their resource management plan. Recognizing that the Geoindicators scoping process could satisfy this request, GRD staff coordinated a scoping meeting with park staff and cooperators (table 1, p. 20). The current Geologic Resource Evaluation Program supercedes the Geoindicators process.

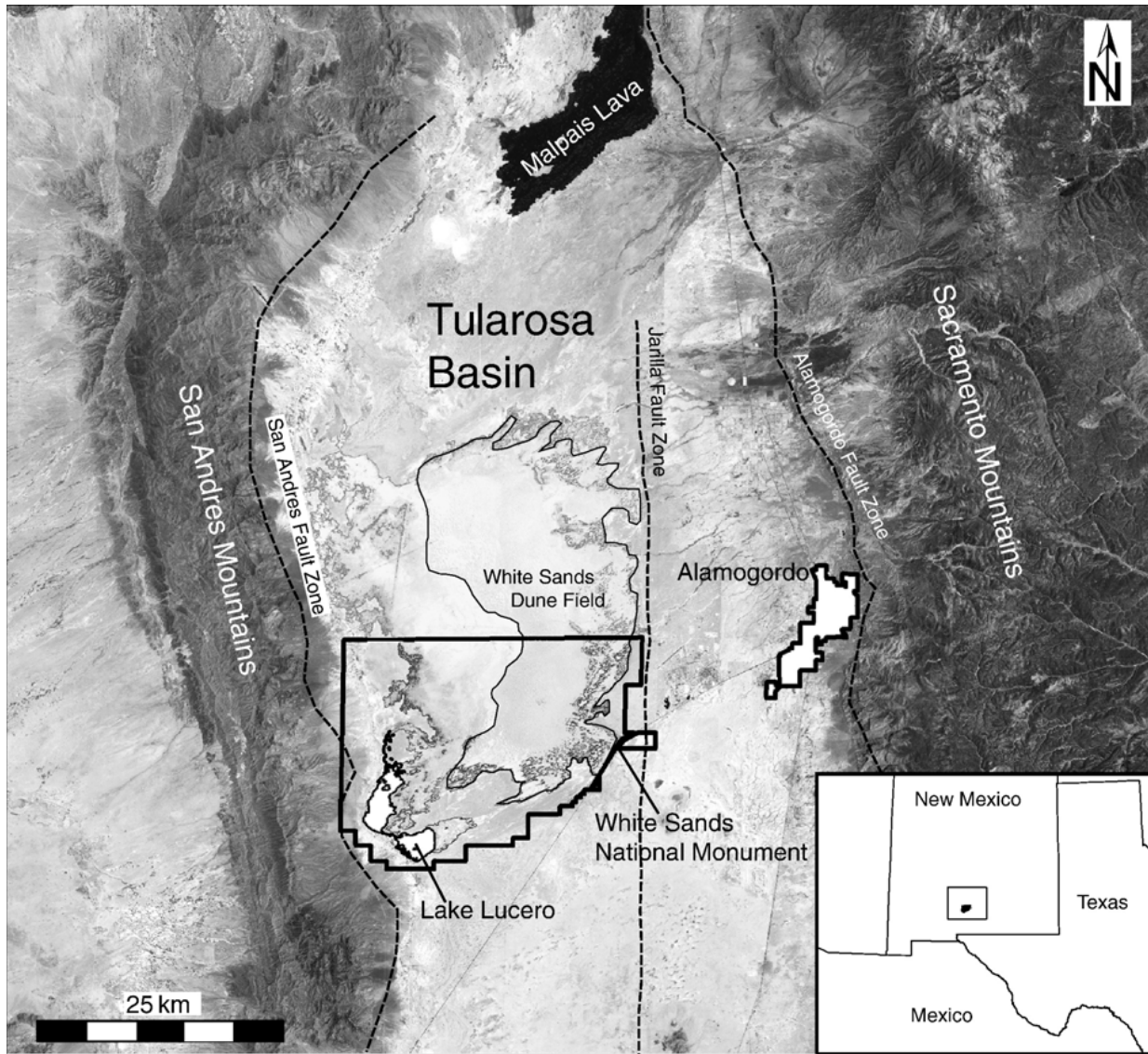
On November 14, 2007, GRE staff and cooperators (table 2, p. 20) convened during a follow-up meeting to ensure all features and processes now discussed as part of the GRE process were adequately covered by the preexisting Geoindicators report. Scoping included a field trip led by David Bustos (White Sands National Monument) for some of the participants on November 13, 2007. Participants also discussed the digital geologic map for the national monument, which the Geoindicators process did not address.

This summary compiles information from the 2003 Geoindicators and the 2007 GRE scoping meetings, including a preliminary plan for producing a digital geologic map for White Sands National Monument.

## Park Setting

White Sands, the largest gypsum dune field in the world, is located in south-central New Mexico at the northern end of the Chihuahuan Desert. In 1931 the National Park Service completed a study of the area's worthiness for inclusion in the National Park System, and on January 18, 1933, outgoing President Herbert Hoover proclaimed 57,867 ha (142,987 ac) of gypsum sands as "White Sands National Monument." The monument is situated in the Tularosa Basin, an internally drained valley flanked by two mountain ranges—Sacramento and San Andres. The entire dune field covers 712 km<sup>2</sup> (275 mi<sup>2</sup>) with about 300 km<sup>2</sup> (115 mi<sup>2</sup>) located within White Sands National Monument. The majority of the dune system is situated in the surrounding White Sands Missile Range, which is not open to the public (fig. 1). As highlighted during the field trip and pre-trip safety video, unexploded ordnance, which inadvertently land in the national monument, is a daily safety concern for visitors and staff.

In the early 1940s the United States government decided that this part of New Mexico was ideal terrain for military operations (Houk and Collier 1994). The Alamogordo Bombing and Gunnery Range was established in 1942, just after the attack on Pearl Harbor. The first atomic bomb test detonation was made at the Trinity Site in 1945, and additional portions of the Tularosa Basin were set aside as White Sands Proving Ground. The Alamogordo Army Air Base, used for aircrew training during World War II, was renamed Holloman Air Force Base after the war. The gunnery range and proving ground were consolidated and renamed White Sands Missile Range in 1958.



**Figure 1.** White Sands Dune Field. White Sands National Monuments hosts approximately 40% of the White Sands dune field, situated in the Tularosa Basin of southern New Mexico. The Tularosa Basin is located within the larger Rio Grande Rift, which are both part the Basin and Range physiographic province. *Source:* Kocurek et al. (2007).

## Geologic Setting

The writer of the final GRE report for White Sands National Monument will prepare a “Geologic History” section. This section will reflect the digital geologic map for the national monument, and highlight each map unit, putting these rocks and unconsolidated deposits into a geologic context. The present setting is a result of at least 11 significant stages of events:

1. Permian Sea and Paleozoic marine rocks, including the Yezo Formation, from which gypsum sand of the White Sands dune system is derived. See Raatz (2002), Kues and Giles (2004), and Mack and Giles (2004).
2. Clastic rocks of the Triassic Period that document terrestrial conditions and uplifting. See Lawton (2004) and Lucas (2004).
3. Cretaceous Interior Seaway and open marine conditions in what is now the Tularosa Basin. See Seager (1981), Molenaar (1983), and Hook and Cobban (2007).

4. Laramide Orogeny and uplifting of marine rocks in southern New Mexico into a giant dome. See Seager et al. (1997).
5. Deposition of sediments (late Cretaceous, Paleocene, and Eocene) on either side of the Rio Grande uplift. See Cather (1991, 2004).
6. Crustal extension of the Rio Grande Rift and associated volcanism, including late-Eocene andesite and dacite and later rhyolite and basaltic andesite. See Seager (1981) and Chapin et al. (2004).
7. Four distinct episodes of Basin and Range extension, including formation of the Tularosa Basin, starting 35 million years ago and continuing today. See Kelley and Chapin (1997) and Mack et al. (2004).
8. Basin fill. See Doty and Cooper (1970), Kelley and Chapin (1997), Seager et al. (1997), and Peterson and Roy (2005).
9. Geomorphic activities of the ancestral Rio Grande. See Seager et al. (1987) and Mack et al. (1996).
10. Formation of Pleistocene playa lakes. See Allen and Anderson (2000), Anderson et al. (2002), Menking et al. (2004), and Allen (2005).
11. Dune formation. See Allen (1991, 1994), Allen and Hawley (1991), Allen and Anderson (1993), Fryberger (1999), and Szyrkiewicz (2008a, b, c, and d).

### **Interpretive Materials**

Geoindicators participants suggested that park managers work with the New Mexico Bureau of Geology and Mineral Resources and other resource experts to develop interpretive materials about the geology of White Sands National Monument. They also suggested that staffs from the national monument, New Mexico Bureau of Geology and Mineral Resources, and other resource experts discuss current issues relative to what visitors typically see at the national monument and prepare interpretive materials based on the outcome of this discussion. Topics may include the consequences of global climate change on dunes; water issues; impact of humans on park conservation efforts; and natural hazards such as dust storms, earthquakes, and debris flows.

### **Contacts**

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- Gary Kocurek, University of Texas–Austin, garyk@mail.utexas.edu, 512-471-5855
- Anna Szyrkiewicz, Indiana University, aszynkie@indiana.edu, 812-855-8034

### **Geologic Mapping Plan**

During the Geoindicators meeting in 2003, participants suggested that a map that identifies the various generations of dunes, ranging from active dunes to the oldest fossil dunes, would be useful for resource management. This map could build on work by Seager et al. (1987) and Fryberger (1999). Investigators would need to collect additional age dates using radiocarbon and thermoluminescence methods and investigate a chronosequence of soil formation on the dunes. Such a study would include vegetative states, desert crusts, soil horizons, and stable isotopic signatures of authigenic soil minerals. Investigation of land surfaces buried by dunes and alluvial sediments west of Lake Lucero would supplement this study. In particular, fossil pollen, phytoliths, and carbon isotopes of paleosols would contain valuable information for an age-dated, geomorphic map.

At the 2007 meeting, participants agreed that Seager et al. (1987) should serve as the digital geologic map for White Sands National Monument. GRE staff will convert the digital data, available from the New Mexico Bureau of Geology and Mineral Resources, to the NPS model. Hildy Reiser (Chihuahuan Desert Network)

requested that the final map product be compatible with the Enterprise GIS system, which the network uses. GRE staff may contact the network's GIS specialist, Scott Schrader, about this system (see table 2).

Nine of the 11 quadrangles of interest for White Sands National Monument are covered in Seager et al. (1987): Tularosa Peak, Heart of the Sands NW, Heart of the Sands NE, Lost River, Heart of the Sands SW, Heart of the Sands, Garton Lake, Lake Lucero, Lake Lucero NE, Foster Lake, and Deadman Canyon. The monument's boundary does not intersect with two of these quadrangles—Tularosa Peak and Deadman Canyon. However, the Tularosa Peak quadrangle is significant because it includes the Lost River drainage, which flows into the national monument and hosts endemic pupfish. The Deadman Canyon quadrangle is significant because White Sands National Monument has rights to the subsurface water, which are necessary for obtaining potable water, in this quadrangle. Hildy Reiser (Chihuahuan Desert Network) mentioned that Holloman Air Force Base has digital data for the Tularosa Peak quadrangle. Dave Love (New Mexico Bureau of Geology and Mineral Resources) mentioned that Dave Koning at the bureau is in the process of mapping the Deadman Canyon quadrangle.

In addition to these data, park staff would like the GRE product to include the 1999 geomorphic map by Steven Fryberger. A PDF of this map (Figure 2-17A) is posted at <http://www2.nature.nps.gov/geology/parks/whsa/geows/Chapter2/fig0217a.pdf>. GRE staff needs to contact Steven Fryberger to inquire about the availability of the "raw data" for inclusion in the digital product (see table 2).

The Department of Defense at White Sands Missile Range has acquired and interpreted satellite imagery of the dune field, playa lakes, and surrounding areas. These data (shapefiles) could likely be shared with the National Park Service if a representative from White Sands National Monument requested them. Bobby Myers ([robert.myers@us.army.mil](mailto:robert.myers@us.army.mil)) is the contact for "all things geologic" at the missile range. He is working with and is the contact for Dave Love and Bruce Allen at the New Mexico Bureau of Geology and Mineral Resources and was a participant at the Geoindicators scoping meeting in 2003.

## **Geologic Resource Management Issues**

During the Geoindicators meeting, participants prioritized the most significant geologic issues at White Sands National Monument as (1) dune features and processes, including dune formation and reactivation, groundwater chemistry in the unsaturated zone, and groundwater level; and (2) lacustrine features and processes, including lake levels and salinity. These are discussed first. Other geologic features and processes of interest to resource managers are listed alphabetically and include the following: climate change, distinctive geologic features, disturbed lands, erosion, fluvial features and processes, geochemistry and geothermal features and processes, hillslope features and processes, karst features and processes, paleontological resources, and seismicity.

### **Dune Features and Processes**

White Sands National Monument is a landscape shaped by the wind. The two principal features in the monument, the gypsum dunes and Lake Lucero, attest to the past and present activity of eolian processes. The dune field consists of a core of crescentic dunes flanked to the north, east, and south by fields of parabolic dunes (Kocurek et al. 2007). Lake Lucero, which occupies the topographically lowest area of the Tularosa Basin, is the largest of the playas. Although partially refilled now, Lake Lucero is an 18-m- (60-ft-) deep depression created by wind erosion.

White Sands is the largest gypsum dune field in the world and is the major driver of the ecosystem and the species within it. For instance, the color of some local populations has adapted to match the sand (e.g., bleached earless lizard, which is shown on the park brochure). Wind, gypsum, groundwater, and vegetation are all significant variables in this dune field ecosystem. In addition to preserving the dunes, managers are

responsible for interpreting the dunes for the public and ensuring public access. An interesting interpretive theme is the analogous nature of White Sands to features on Mars, which researchers from NASA and the University of California–Davis are studying (see Chavdarian and Sumner 2006). In order to keep the dunes accessible to all visitors, staff time is used to keep the Loop Road open, which is constantly affected by eolian processes. “Plowing” of the road causes lowering of the dune drive area, resulting in flooding and road closure during wet periods. GRE scoping participants suggested “infilling” as a road-maintenance alternative; Holloman Air Force Base uses this method. Comparison of lidar images may show downcutting related to road maintenance. Wind erosion is a consideration in future development of facilities and maintenance of current facilities (e.g., roads, trails, fences, and restrooms). Additionally, wind erosion impacts cultural resources such as hearth sites.

An interesting, possibly climate-related, development is the noticeable lack of dome dunes at White Sands National Monument. The park brochure still discusses these features as part of the landscape and identifies them as the first dune type to form downwind of Lake Lucero. Other distinctive features still active on the landscape are yardangs and the tall, pipe-like accumulations of coarse gypsum called crystal pedestals (see “Distinctive Geologic Features” section).

Introduced into the United States in the early 1900s as a wind break, salt cedar creates vegetative pedestals by drying out the surrounding sand, which erodes away. Salt cedar changes local wind patterns and causes dunes to form by trapping sand in front of the “natural” dune field.

An adequate understanding of dune formation and reactivation includes the relationship with groundwater. Vegetation and soil crusts also play roles in dune stability, but groundwater level is the primary determinant for dune activity and stability. If the water table is lowered through natural or anthropogenic means, the dunes will become more active. Dune stability is a function of the capillary attraction of groundwater and the wicking nature of sand in the unsaturated zone. Groundwater in the unsaturated zone and the associated water-holding capacity of the dunes are important for plants, burrowing animals, and soil formation. Depending on the durability of the interdune surface crust, fewer plants may be present and more wind erosion may occur. In the context of the ecosystem of White Sands National Monument, the unsaturated zone is highly significant and includes not only groundwater chemistry but physical and microbiotic components.

Although groundwater quality is poor for consumption, it is important to dune formation and reactivation. The highly saline groundwater affects production of gypsum, which is the primary constituent of the dunes. If the salinity balance is changed, the dune system is changed. In short, less salinity in the dune system results in less gypsum and less material for dune formation. The saline groundwater also precipitates minerals within the windblown sand.

Current research by Anna Szyrkiewicz, Gary Kocurek, and Rip Langford is illuminating the origin and timing of dune formation, dune dynamics, and the interactions between eolian deflation and playa lakes. The Heart of Sands quadrangle, Kocurek’s study area, includes all dune types. Kocurek and Langford are writing the monitoring protocol for dune dynamics, and Langford and Szyrkiewicz are creating conceptual models for the gypsum sand dunes at White Sands National Monument and Guadalupe Mountains National Park. Kocurek and colleagues have baseline lidar data acquired in 2007.

### **Lacustrine Features and Processes**

After the dunes, Lake Lucero is the most important asset at White Sands National Monument. The shallow lake is concentrated in the deepest part of the basin. The lake level and salinity of Lake Lucero are controlled by evapotranspiration and leakage to the water table. Although the ultimate source of gypsum is the Paleozoic-age rocks exposed in the surrounding mountains to the west, north, and east of the national monument, the dune system is Quaternary in age, and the sand is derived through deflation of evaporite beds

of Lake Otero and younger playa lakes (Kocurek et al. 2007). Wave action breaks down the gypsum crystals that form in the lake beds.

Lake Lucero provides habitat for migrating birds, invertebrates such as fairy shrimp, and modern diatoms, ostracodes, and foraminifera. Spadefoot toads, which burrow into the lake sediments during dry periods, “erupt” when wet conditions return. As such an important component of the dune system, contamination of Lake Lucero from missile-range tests during flooding events on Alkali Flats is a particular management concern.

Being able to accurately interpret Lake Lucero and the source of gypsum sand is quite significant, so research on the lake beds continues to be a management need. Research findings on Lake Lucero will have a major influence on interpretive materials and presentations.

### **Climate Change**

“A climate disrupted by human activities poses such sweeping threats to the scenery, natural and cultural resources, and wildlife of the West’s national parks that it dwarfs all previous risks to these American treasures,” so states the July 2006 report, “Losing Ground: Western National Parks Endangered by Climate Disruption” (Saunders et al. 2006). The authors contend that “a disrupted climate is the single greatest threat to ever face western national parks.” Because of the potential disruption that climate change could cause to park resources, including geologic features and processes, the GRE Program has begun to include a discussion of the effects of climate change to park resources during scoping meetings. Climate change could have a dramatic effect on the dune system at White Sands National Monument. Warmer, drier conditions could result in larger deflation areas and less vegetation to stabilize existing dunes; reactivation of dunes could occur with potentially larger dunes forming; a drop in the water table would impact dune formation; less runoff available to feed Lake Lucero would create more dunes moving out of the lake beds.

### **Distinctive Geologic Features**

Distinctive geologic features such as dunes and Lake Lucero will be discussed at length in the final GRE report. Here some less apparent features identified during Geoindicators and GRE scoping are highlighted.

#### ***Soil Crusts***

Soil crust occupies an intermediate ecological position between active dunes and heavily vegetated surfaces in White Sands National Monument. Soil crusts are indicators of ecosystem stability, health, and climate change. They are critical to plant growth because they fix nitrogen into the system and bind soil. Soil crusts can either promote water infiltration (on silty soils) or increase runoff (on sandy soils). Both these attributes are important for the dune ecosystem. Filaments of cyanobacteria are hydrophobic, so crusts made of cyanobacteria promote lateral redistribution of water.

Soil crusts in White Sands National Monument appear robust, and potential problems are unknown. According to Curtis Monger (White Sands National Monument), crusts in sulfate-rich soils form quickly (within a few years) so that foot-traffic disturbances are less likely to create long-term problems (Dave Love, New Mexico Bureau of Geology and Mineral Resources, written communication, May 16, 2008).

#### ***Wetlands***

Wetlands serve as an indicator of long-term precipitation trends. In desert environments, the scarcity of water underscores the significance of wetlands. Anecdotal evidence indicates that wetlands and wetland species are being lost at White Sands National Monument, apparently as a result of drought. Certain wetland species seemed much more abundant in the recent past; for example, park staff regularly heard frogs from the housing area in the 1980s. Though opportunities for mitigation are minimal because wetlands are naturally driven systems with few human impacts at the national monument, managers are concerned about the loss of

wetlands. Typically, wetlands are areas of high biodiversity, and the scarcity of wetlands increases their importance to plants and wildlife as a source of water.

### *Yardangs*

According to Steven Fryberger, White Sands is a premier U.S. site for erosional hills called yardangs. Often shaped like the hulls of boats, the variety at White Sands is great (Steven Fryberger, e-mail communication, December 25, 2007). Unfortunately, most visitors will never see these features because the best examples are not publically accessible. Yet they are worth noting as part of the entire system. A few pictures of these features are posted at <http://www2.nature.nps.gov/geology/parks/whsa/geows/Chapter8.htm#sec5>.

### *Pedestals*

An unreported scientific debate is occurring as a result of the curious pedestals, which reach 4.5 m (15 ft) tall and 12 m (40 ft) wide, on the Alkali Flats (fig. 4). These features appear aligned along folds in the lake beds. Dave Love (New Mexico Bureau of Geology and Mineral Resources) is one of the participants in this debate among researchers at White Sands.



**Figure 4.** Crystal Pedestals. NPS photo/David Bustos.

### **Disturbed Lands**

Modern human activities have disturbed more than 315,000 acres (127,480 ha) in 195 National Park System units. Some of these features may be of historical significance, but most are not in keeping with the mandates of the National Park Service. Disturbed lands are those park lands where the natural conditions and processes have been directly impacted by mining, development (e.g., facilities, roads, dams, abandoned campgrounds, and user trails), agriculture (e.g., farming, grazing, timber harvest, and abandoned irrigation ditches), overuse, or inappropriate use. Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, hurricanes, tornadoes, and fires are not considered for restoration unless influenced by human activities.

Restoration activities return the quality and quantity of an area, watershed, or landscape to some previous condition, often some desirable historic baseline. Restoration at disturbed areas directly treats the disturbance to accelerate site recovery and should aim to permanently resolve the disturbance and its effects. For more

information about disturbed lands restoration, contact Dave Steensen (Geologic Resources Division) at [dave\\_steensen@nps.gov](mailto:dave_steensen@nps.gov) or 303-969-2014.

Impact craters from renegade bombs are a unique disturbance at White Sands National Monument. A particular geologic curiosity associated with bomb impacts is anthropogenic fulgurite, in this case melted gypsum. Natural fulgurite forms via lightning strikes on mountain tops or dune areas.

Quarries for soda ash and gypsum, as well as a plaster of paris plant and a trail to a salt mine, are legacies of mineral exploration and development at the national monument. Disturbance is minimal at these sites and none require reclamation. The sediments are breaking down naturally, removing traces of mining activities. Though never developed, the Department of Defense investigated oil and gas potential at White Sands Missile Range. No oil and gas leasing occurs at White Sands National Monument.

## **Erosion**

Geoindicators participants suggested that changes in plant communities at White Sands National Monument are partly a result of historic ranching practices, which led to overgrazing and ultimately erosion. Other past land-use practices may also be drivers of increased soil erosion, for example the introduction of invasive plants and animals and fire suppression (Pete Biggam, GRD soil scientist, written communication, January 11, 2008).

Erosion is a natural process, but concern arises when erosion is anthropogenic and detrimental to park resources. For instance, poorly engineered culverts on roads, particularly on the west side, have caused accelerated erosion and downcutting, which has damaged cultural resources such as the Huntington Site, an archaeological site in the northwest corner of the monument. Erosion is an issue for park managers as they come into compliance with standards for archaeological sites. In addition, fiber optic cables, which are cut and buried in straight lines, serve as “speedways” for water. A concentration of runoff along old roads and trails on the west-side bajadas is notable. For example, several areas of gully erosion occur along the trail east to Lake Lucero; road culverts or fiber-optic lines are not the cause of accelerated erosion in this location.

## **Fluvial Features and Processes**

During the Geoindicators scoping session in 2003, discussion of fluvial features and processes (i.e., streamflow) concentrated on Lost River, an ephemeral stream and the only stream that enters White Sands National Monument. In 2007, as a result of a boundary change, about 105 km (65 mi) of intermittent streams, which enter from the west, dissect the national monument. Periodically either migrating dunes block streamflow into the monument or create new pathways. Pupfish—a state-listed threatened species—live in the Lost River. In 2003 no pupfish inhabited the monument; however, as a result of shifting dunes, the course of the Lost River changed in the last few years, bringing pupfish with it.

The City of Alamogordo and ranching activities have dewatered Lost River. Spring boxes in the Sacramento Mountains now intercept water that historically would have flowed into Lost River. Population growth in the area has caused increased water use and lowered water levels of Lost River.

Annual rainfall cycles, which include extreme storm events, affect streamflow and surface water. Annual rainfall cycles also impact cyanobacteria blooms, plant and animal species, and the playa system. During wet periods Lost River may transport perchlorate from rocket fuel into the monument; Holloman Air Force Base hosts a 10-km- (10-mi-) long, high-speed track for rocket tests on the Lost River playa.

## **Geochemistry and Geothermal Features**

Anna Szykiewicz, a postdoctoral fellow at Indiana University, is studying sulfur, oxygen, and hydrogen isotopes from the sediments at White Sands National Monument. Her findings will be significant for dating



dune features, establishing the timing of eolian processes, and possibly indicating hydrothermal activity at the national monument. Known geothermal activity in the northern Tularosa Basin associated with the Malpais volcanics suggests the potential at the national monument.

### **Hillslope Features and Processes**

The piedmont landforms, called bajadas, are evidence of hillslope processes. Bajadas are a coalesced system of alluvial fans; they form as debris flows at the base of the San Andres Mountains. During sudden rainfall events of up to 20 cm (8 in) per hour, debris flows become activated and are a safety concern. Debris flows have killed people on the missile range and in a nearby BLM campground. The west side of the basin has no shorelines because hillslope processes eroded them. Bajadas distribute water, have distinct plant communities and soil types, and are the recharge area for water to the basin. Hillslope processes transport large boulders onto the roads in the monument and periodically knock out sections of the perimeter fence.

Military-owned roads and culverts upslope of the national monument have changed the flow regime that originates in the bajada areas along the western boundary. Roads serve as berms and inhibit surface flow across the alkali flats area. Culverts concentrate flow and increase erosion. Of particular concern is erosion of archaeological sites impacted by runoff from under-engineered roads, primarily during storm events, and water pathways created by fiber optic lines. The principal damage has been done to these sites, so damage is now incremental. However, managers want to mitigate further damage to these sites is a management concern.

### **Karst Features and Processes**

Karst-like natural dissolution frequently occurs in the cemented gypsic and calcic soils of the Tularosa Basin, resulting in collapsed areas with little if any prior surface indication. Openings such as desiccation cracks or animal burrows provide starting points where water collection causes significant subsurface dissolution. Karst occurs in the Tularosa Peak quadrangle, north of the monument; investigators have not found karst in the monument, however. A perched water table and the absence of flow-through water in the Alkali Flats area probably prohibit karst formation.

Human activities have caused an artificial form of karstification in the monument. Buried water and utility lines and poorly compacted construction excavations provide a less-dense matrix that increases water infiltration and saturation below grade. Inadvertent leaks of water lines exacerbate this condition. The water, whether from natural sources or leaks, dissolves the gypsum. One noteworthy example at the monument is the formation of a sink hole as a result of an air conditioner leak. At White Sands National Monument and nearby developed areas such as Holloman, this process is undercutting the edges of parking lots, curbs, utility trenches, and buildings. The monument's historic visitor center appears to be subsiding, possibly as a result of dissolution but more likely on account of sheer mass and soil compaction. Stabilizing the visitor center and mitigating further water leaks are important with respect to the overall maintenance of park facilities.

### **Paleontological Resources**

Greg McDonald, former paleontologist for the Geologic Resources Division, summarized the paleontological resources at White Sands National Monument after the Geoindicators meeting in 2003. That information is included here and augmented with more recent discoveries discussed during GRE scoping in 2007. Recent findings highlight the potential for paleontological resources at the national monument; nevertheless, neither the National Park Service nor its cooperators have conducted a thorough inventory (see "Inventory Paleontological Resources," p. 13).

Investigators have found Pleistocene fossil vertebrates and mollusks at a number of localities in White Sands Missile Range just north of the monument (Lucas et al. 2002; Morgan and Lucas 2002). These fossils were recovered from clays of the Otero Formation, which were deposited as a large pluvial lake called Lake Otero

that covered a large portion of the Tularosa Basin (Lucas and Hawley 2002). Lake Lucero in the monument is a remnant of Lake Otero, and lake sediments similar to those in the missile range are present in the northwest part of the monument. Lake sediments within the monument likely contain Pleistocene vertebrates, invertebrates, and plants (Greg McDonald, Geologic Resources Division, written communication, 2003).

Researchers have documented late Pleistocene footprints of mammoths at White Sands National Monument (e.g., Lucas et al. 2007). The tracks are preserved in convex relief in a soft gypsum matrix. They are extremely fragile and easily eroded. On November 13, 2007, David Bustos (White Sands National Monument) showed GRE participants one of the mammoth tracksites on the shores of Lake Lucero. Investigators estimate the tracks to be 30,000–40,000 years old, but radiocarbon dates are needed to verify the ages of these lake beds (Dave Love, New Mexico Bureau of Geology and Mineral Resources, oral communication during GRE scoping, November 14, 2007).

Lake sediments also contain microfossils. Bruce Allen has successfully separated many microfossils from Lake Otero sediments and has obtained radiocarbon ages from a sequence of lake beds from two episodes of lake formation and between-lake erosion ranging from more than 40,000 years to about 15,000 years ago. When properly collected and processed, microfossils such as ostracodes or diatoms could provide important paleoecological information (Greg McDonald, Geologic Resources Division, personal communication, 2003). Based on similar geologic units to the north of the monument, GRE participants suggested that fossil pupfish, amphibians, and snails may also occur within monument boundaries. Since the GRE scoping meeting in November 2007, investigators have found possible pupfish bones and scales in Lake Otero sediments (Dave Love, New Mexico Bureau of Geology and Mineral Resources, written communication, May 16, 2008).]

Because of security precautions at White Sands Missile Range, Pleistocene Lake Otero has not been as accessible as pluvial lakes in other basins in New Mexico. Consequently scientific knowledge of the history of this Pleistocene pluvial lake is not as extensive as that of Lake Estancia to the north. Studies at Lake Estancia (e.g., Bachhuber 1990, Behnke and Platts 1990, Frenzel 1992, and Allen 1996) have demonstrated the wealth of climatic data contained in these lake sediments. Similar studies of Lake Otero sediments would provide equally valuable information (Greg McDonald, Geologic Resources Division, written communication, 2003). While the portion of Lake Otero sediments preserved at White Sands National Monument is small compared to the overall size of the lake, the monument portion is critical because it preserves the latest part of the history of Lake Otero, particularly the progressive decrease in size to its remnant Lake Lucero. Anna Szyrkiewicz has several abstracts documenting the changes in sulfur isotopes in the lake beds and the way deflation of Lake Otero sediments furnished gypsum to the dunes downwind (e.g., Szyrkiewicz 2008a, b, and c). In addition to providing critical information on the geologic history of the national monument and the formation of its primary resource (i.e., sand dunes), knowledge of the history of Lake Otero would provide an important framework for understanding the paleoecological context of early people in the basin.

Related to Pleistocene stratigraphy is the possibility of finding two episodes of micrometeorite falls in the Tularosa Basin: one dated about 12,900 years is found southwest and northeast of the Tularosa Basin in the “Clovis black mat” layer in archaeological sites; this layer appears to be exposed in the Tularosa Basin (see Firestone et al. 2007). A second episode of micrometeorites that impacted mammoths and bison in the arctic about 35,000 years ago might be found in Lake Otero beds (Dave Love, New Mexico Geological Survey, written communication, May 16, 2008).

## **Seismicity**

Faults on both sides of the Tularosa Basin have associated seismic events. The Alamogordo Fault at the base of the Sacramento Mountains flanks the east side of the basin; the San Andres Fault flanks the west (see fig. 1). In addition to faults, Seager et al. (1987) shows folds in the lake beds. Koning and Pazzaglia (2003) report

on the paleoseismicity of the Alamogordo Fault. Salyards (1991) provides a preliminary assessment of the seismic hazard of the southern Rio Grande Rift. The nearest seismic stations are southeast of Socorro, New Mexico, and at Dagger Draw near Carlsbad, New Mexico. GRE participants agreed that seismic risk for health and human safety is low at the national monument.

Seismic hazard maps from the U.S. Geological Survey are available at [http://earthquake.usgs.gov/research/hazmaps/products\\_data/2008/maps/](http://earthquake.usgs.gov/research/hazmaps/products_data/2008/maps/); one of the maps for New Mexico also includes some faults (see [http://earthquake.usgs.gov/research/hazmaps/products\\_data/2008/maps/wus/nm/5hzSA.NM.jpg](http://earthquake.usgs.gov/research/hazmaps/products_data/2008/maps/wus/nm/5hzSA.NM.jpg)).

## Recommendations

The following is a list of recommendations gathered during the Geoindicators meeting in 2003, including recommendations for inventory, monitoring, research, and mitigation. Recommendations are not listed in any order of priority.

### Inventory

#### *Gather Baseline Information about Groundwater Level*

The current and future need for water may affect shallow groundwater levels at White Sands National Monument. Research has identified groundwater level as a major controlling factor on dune activity. Therefore, gathering baseline data on groundwater level to distinguish human use/drawdown from natural (seasonal and annual) fluctuations is important. Park managers need basic information about the local aquifers to respond in an informed way to the growth and development in the Tularosa Basin and the effects on park resources. Bobby Myers at White Sands Missile Range is a contact for hydrological data.

#### *Compile References and Data about Dunes*

A useful place to start in order to better understand dune processes is compiling and organizing available information. The body of literature about the dunes is likely to be substantial and will contain some classic works (e.g., McKee 1966, 1971, and 1979). Information will also include aerial photographs and satellite images.

Participants at the Geoindicators meeting suggested that an upper-level undergraduate or graduate student—possibly students for Gary Kocurek or Rip Landford—with training in eolian geomorphology could complete this task and provide necessary annotations and explanations to park staff. Funding for such a project may be available through the GeoScientists-in-the-Parks (GIP) Program.

#### Contact

- Lisa Norby, Geologic Resources Division, GIP program manager, [lisa\\_norby@nps.gov](mailto:lisa_norby@nps.gov), 303-969-2318

#### *Inventory Soils*

The scale at which the existing soils map (Neher and Bailey 1976) was produced is not useful for making management decisions. Geoindicators participants suggested that White Sands National Monument be remapped at a more useful scale. The mapping project should include physical and biological soil crusts. As of May 2008, the Natural Resource Conservation Service (NRCS) was in the process of updating the soils map of the Tularosa Basin (Dave Love, New Mexico Bureau of Geology and Mineral Resources, written communication, May 16, 2008).

The digital geologic map product produced by the GRE Program will not include soils; however, the NPS Soils Program is part of the Geologic Resources Division, and park staff can express needs to Pete Biggam at [pete\\_biggam@nps.gov](mailto:pete_biggam@nps.gov) or 303-987-6948.

#### Additional Resources

- Soil Quality Institute in Las Cruces
- Jornada Experimental Range Station

#### *Gather Baseline Formation about Surface Water Quality*

Park managers lack information about the effects of surface water quality on the ecosystem, and human influences are unknown. In general, water quality, which is poor for consumption, is dominated by the close proximity of gypsum to the surface, interior drainage, and climatic factors such as the dominance of evaporation. Approaches to inventorying surface water quality will be strongly influenced by sporadic precipitation/runoff events, which may momentarily improve overall water quality by dilution. The ephemeral nature of surface water at White Sands National Monument makes sampling for surface water quality difficult. The U.S. Geological Survey uses innovative techniques such as sampling the leaves of salt cedar near Lost River. Sources of contaminants may be limited to nearby military facilities.

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- Robert Myers, White Sands Missile Range, [myersr@wsmr.army.mil](mailto:myersr@wsmr.army.mil), 575-678-8751

#### *Compile Information about Biological Soil Crusts*

Various applicable sources of information about biological soil crusts include (1) data from vegetation plots in White Sands Missile Range, (2) data from Holloman Air Force Base, (3) data from a study of ATV tracks in 2000 and 2002 in the monument, and (4) AVIRIS imagery from University of Texas–El Paso.

Geoindicators participants suggested that a database of this information be developed in order to analyze what is known about resilience, recovery rates, overall spatial distribution, and spatial distribution of various types of biological soil crusts.

A possible plan of action could use samples of the biological soil crusts, which are growing in a laboratory setting at New Mexico State University. Investigators “image” these samples in a laboratory at University of Texas–El Paso to obtain the spectra of wet samples. After the spectra are obtained, watering stops, and investigators image the crusts as they dry out. In this way, a database is established to help interpret the satellite imagery. The AVIRIS image is for one point in time. The information gained from this method may extend to other satellite platforms that are more commonly available than AVIRIS.

#### Contacts

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- Phil Goodell, University of Texas–El Paso, [goodell@utep.edu](mailto:goodell@utep.edu), 915-747-5968
- Curtis Monger, New Mexico State University, [cmonger@nmsu.edu](mailto:cmonger@nmsu.edu), 505-646-1910

#### *Inventory Wetlands*

Neither the National Park Service nor its cooperators have conducted a comprehensive inventory of wetlands, but anecdotal evidence indicates that wetlands, and thereby wetland species, are being lost. If an inventory of wetlands is undertaken, Geoindicators participants suggested that park managers adapt the protocols and classification used in a nine-year study at the White Sands Missile Range. Aerial photographs from the 1940s, 1984, and 1996 may be useful background information for an inventory of wetlands.

#### Contact

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### *Inventory Paleontological Resources*

*Paleontological Resource Inventory and Monitoring, Chihuahuan Desert Network* (i.e., Santucci et al. 2007) compiles paleontological resource data for White Sands and includes cited and additional references. However, a thorough survey of paleontological resources including field work at White Sands National Monument is needed. Paleontologists at the New Mexico Museum of Natural History and Science have expressed an interest in providing this survey for fossil vertebrates and larger invertebrates. Bruce Allen (New Mexico Bureau of Geology and Mineral Resources) has expressed interest in conducting a study of fossil micro-invertebrates in Lake Otero sediments in the northwest corner of the national monument.

Based on results of these studies, park staff could be involved in a larger Lake Otero basin study, which would be a cooperative project among the New Mexico Museum of Natural History and Science, New Mexico Bureau of Geology and Mineral Resources, White Sands Missile Range, and White Sands National Monument. The goal of the project would be to look at the paleoecology and paleontology of the basin related to climatic change during the Pleistocene.

### **Monitoring**

#### *Monitor Lake Levels and Salinity of Lake Lucero*

Lake Lucero is an integral part of the dune ecosystem and is linked to the regional groundwater system. Monitoring of lake levels and salinity would provide insight into the interrelationships among Lake Lucero, dune processes, and groundwater. Information gained through monitoring would help answer many questions: (1) What salts are produced in Lake Lucero? (2) When are they produced? (3) What are the relative amounts of groundwater and surface water? (4) How do changes in lake level affect salinity? (5) How do lake levels correspond to the regional water-table aquifer and to potential perched aquifer(s) of the dune field?

Geoscientists participants suggested that a team of subject and resource experts be formed to develop a monitoring program for Lake Lucero. Potential members include

- Rip Langford, University of Texas–El Paso, langford@utep.edu, 915-747-5968
- Andrew Valdez, Great Sand Dunes National Park, andrew\_valdez@nps.gov, 719-378-2312
- Anne-Marie Matherne, U.S. Geological Survey, Albuquerque, amatherne@usgs.gov, 505-830-7971
- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950

#### *Monitor Extreme Storm Events*

The ephemeral nature of surface water at White Sands National Monument makes sampling difficult. In order to adequately record “vital statistics” (e.g., amount, quality, and duration) of surface water in the monument, a specialized approach needs to be taken. Summer storm events, in which the majority of annual precipitation falls, need to be monitored. Because storms are localized, a SWAT approach may be useful. Additionally using crest stage gages to measure streamflow in inaccessible areas should be considered.

#### **Contacts**

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- Pete Penoyer, NPS Water Resources Division, pete\_penoyer@nps.gov, 970-225-3535

#### *Monitor Groundwater Level and Quality*

Scientists and park managers have recognized the importance of groundwater to the ecosystem, but the actual mechanics and processes need to be better understood. Basic data such as groundwater level and quality would enhance the overall information base of the national monument. A network of monitoring wells could be established; the six existing wells in White Sands National Monument could be used more extensively for

data gathering. The National Park Service has established such a network in Great Sand Dunes National Park, which could serve as a model for White Sands. Monitoring should capture seasonal cycles.

#### Contacts

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- Bruce Allen, New Mexico Bureau of Geology and Mineral Resources, [allenb@gis.nmt.edu](mailto:allenb@gis.nmt.edu), 505-366-2531
- Andrew Valdez, Great Sand Dunes National Park, [andrew\\_valdez@nps.gov](mailto:andrew_valdez@nps.gov), 719-378-2312

#### *Monitor Gully Erosion along Trails and Roads*

Geoindicators participants suggested that park managers address accelerated erosion along trails; for example, the gullies along the trail to Lake Lucero reveal fresh exposures, which could provide more information about Lake Otero or fossils in lake deposits. These exposures may also provide interpretive opportunities during walks to Lake Lucero. Beginning to document present changes would help with future interpretive signs (i.e., historic changes of the bajada).

#### Contact

- Dave Love, New Mexico Bureau of Geology and Mineral Resources, [dave@gis.nmt.edu](mailto:dave@gis.nmt.edu), 505-835-5146

### Research

#### *Study Sediment Sequence and Composition*

Sediment sequence and composition is a tool that can provide necessary background information and a past context of both natural processes and human activities. Geoindicators participants identified the analysis of sediment sequence and composition as a means for understanding long-term trends in an ecosystem and identifying human influences on the ecosystem. As such, sediment sequence and composition can provide information for management decisions and planning. Sediment cores that record the evolution of Lake Lucero contain historical and baseline data that would be useful for resource management, park planning, and interpretation.

#### *Study the Relationship between Dunes and Groundwater*

Geoindicators participants identified the need for better understanding of the relationship between dune processes and groundwater dynamics. Anecdotal evidence indicates that the unsaturated zone is significant for dune stability, but the mechanism is not well understood. Geoindicators participants suspected that the high salinity content of the groundwater is important for gypsum production and dune formation, but again the mechanism needs further study. Studying the local, possibly perched, groundwater conditions of the dune field may provide a broader understanding of the groundwater resources of the basin.

A regional, basin-wide conceptual model needs to be developed in order to better understand groundwater dynamics and its relationship to the overall eolian system. At the time of Geoindicators scoping in 2003, the U.S. Geological Survey was in the process of developing a groundwater model for the Tularosa Basin; the first draft was under review, but completion was anticipated to take a year or more. Once this regional model is completed, participants thought “telescoping” to the park-scale was possible. This groundwater model would be part of a model of the entire eolian system.

Geoindicators participants suggested that park staff solicit scientists to submit research proposals for consideration. The Inventory and Monitoring Program and other NPS sources, as well as cooperative scientific efforts and cost-share agreements with partners (e.g., U.S. Geological Survey, U.S. Department of Defense, New Mexico Bureau of Geology and Mineral Resources, and area universities), are possible sources of funding.

#### Contacts

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#### *Study Present Significance and History of Lake Lucero*

Lake Lucero and its Pleistocene predecessor Lake Otero have an interesting geologic history that requires further study in order to fully understand their importance to the Tularosa Basin and White Sands National Monument. Information gained from an in-depth study of Lake Lucero would allow park staff to better understand, manage, and interpret this resource. Information would also aid in understanding the present dynamics of Lake Lucero, which factor into dust storms and the timing and production of salts.

Extracting and analyzing a sediment core from Lake Lucero would be a significant step toward determining Lake Lucero's history and evolution. A multi-disciplinary approach that includes stratigraphy, mineralogy, palynology, limnology, and micropaleontology would result in the most information. Some fraction of the core should be retained for future analysis and interpretive and educational display purposes at the national monument. Such data would provide needed background information and a past context of both natural processes and human activities.

#### Contacts

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#### **Mitigation**

##### *Mitigate Further Damage to Archaeological Sites Caused by Human-Induced Erosion*

Roads under-engineered for extreme storm events and fiber optic lines have caused erosion to archaeological sites in the monument. The principal damage from Range Road 7 to these sites has been done, and damage is now incremental. Old fiber optic cables will likely be repaired and replaced and new cable added, rather than the road being modified. Repairing, replacing, and adding fiber optic cables has more potential to introduce new damage than erosion caused by roads, which continues at a more moderate rate.

Park managers want to mitigate further damage to cultural resources. Geoindicators participants identified the potential for a partnership between White Sands National Monument and White Sands Missile Range and suggested that park staff pursue this opportunity.

#### Contacts

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- Robert G. Myers, White Sands Missile Range, myersr@wsmr.army.mil, 505-678-8751

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**Table 1. Participants at 2003 Geoindicators Meeting**

**White Sands National Monument**

Bill Conrod, Natural Resource Specialist  
Kathy Denton, Education Specialist  
Jessica Kusky, Interpreter  
Julie Lockhard, Student Conservation Association Intern  
Jim Mack, Superintendent  
John Mangimeli, Chief of Interpretation  
Diane White, Cultural Resource Specialist

**National Park Service**

Bob Higgins, Geologic Resources Division  
Greg McDonald, Geologic Resources Division  
Lisa Norby, Geologic Resources Division  
Pete Penoyer, Water Resources Division  
Andrew Valdez, Great Sand Dunes National Park  
Bill Reid, Chihuahuan Desert Network

**New Mexico Bureau of Geology and Mineral Resources**

Bruce Allen, Field Geologist  
Dave Love, Principal Senior Environmental Geologist  
Greer Price, Senior Geologist/Chief Editor  
Peter Scholle, Director/State Geologist

**U.S. Geological Survey**

Rick Huff, Las Cruces  
Anne-Marie Matherne, Albuquerque  
Holloman Air Force Base  
Andrew “JR” Gomolak, Geologist/Archaeologist  
Rich Wareing, Chief of Environmental Analysis

**Other Participants**

Phil Goodell, University of Texas–El Paso  
Adrian Hunt, New Mexico Museum of Natural History and Science  
Katie KellerLynn, Geologist/NPS Contractor  
Rip Langford, University of Texas–El Paso  
Curtis Monger, New Mexico State University  
Robert Myers, White Sands Missile Range

**Table 2. GRE Cooperators for White Sands National Monument**

Name	Affiliation	Position	Phone	E-Mail
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Rip Langford	University of Texas–El Paso	Professor	915-747-5968	langford@utep.edu
Dave Love	New Mexico Bureau of Geology and Mineral Resources	Geologist	575-835-5146	dave@gis.nmt.edu
Gordon Michaud	USDA Natural Resource Conservation Service	Soil Scientist	575-522-8775 x. 129	gordon.michaud@nm.usda.gov
Hildy Reiser	Chihuahuan Desert Network	Network Coordinator	575-646-5294	hildy_reiser@nps.gov
Scott Schrader	Chihuahuan Desert Network	GIS Specialist	575-646-5022	schrader@nmsu.edu
Anna Szynkiewicz	Indiana University	Postdoctoral Fellow	812-855-8034	aszynkie@indiana.edu